Meta-stable SUSY Breaking Vacua in Supersymmetric Gauge Theories

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Until recently, it has been believed that dynamical SUSY breaking is special

- Witten index
- $U(1)_R$ symmetry

Dynamical supersymmetry breaking is not special but seems generic

[Intriligator-Seiberg-Shih `06]

New avenue

- long-live meta-stable vacuum
- explicit breaking of $U(1)_R$
- simple
- vector-like model
- string embedding

It's time to revisit model building

$SU(N_C)$ SQCD in Free magnetic Range

$$N_C + 1 \leq N_F < \frac{3}{2} N_C$$

- Dual description is $SU(N_F\text{-}N_C)$ SQCD with singlet

$$W_{mag} = M\tilde{q}q$$

- Kahler potential is almost canonical

$$K_{IR} = \frac{1}{\alpha} Tr M^\dagger M + \frac{1}{\beta} Tr(q^\dagger q + \tilde{q}^\dagger q) + \cdots$$

- Small mass term makes vacuum structure rich

$$W_{mag} = M\tilde{q}q + \mu^2 M \qquad \mu^2 = m_Q \Lambda_e$$

- F-term condition for M can not be satisfied

$$q^c_g \tilde{q}^f_c + \mu^2 \delta^f_g = 0$$

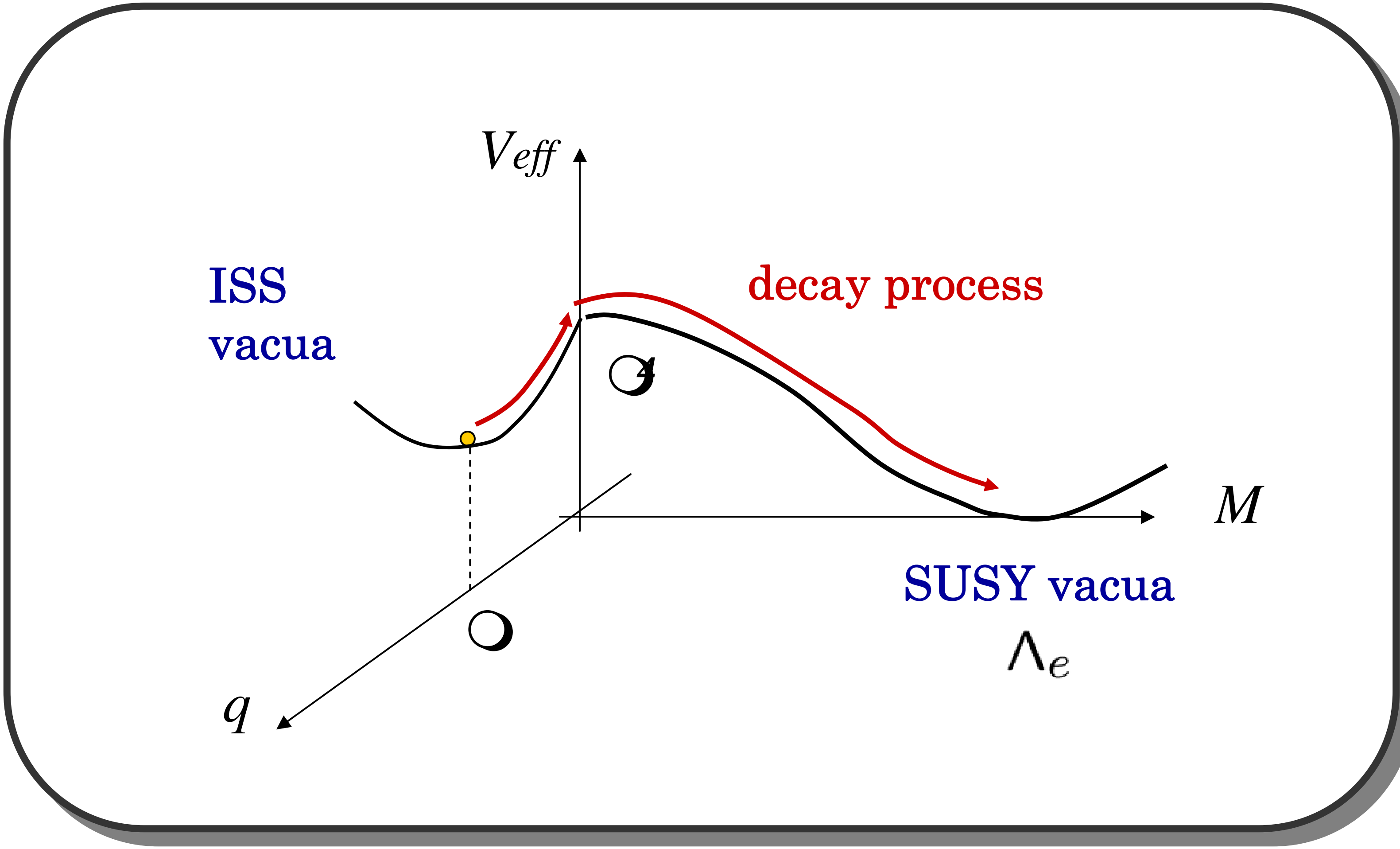
Rank N_F-N_c Rank N_F

- Supersymmetry is broken at tree level
- Solution for all the D and F-term conditions has non-compact flat direction (❑, M_0)

$$q = \begin{pmatrix} \mu e^{\theta} \\ 0 \end{pmatrix} \qquad \tilde{q} = \left(\underbrace{\mu e^{-\theta}}_{N_F-N_c} \ \underbrace{0}_{N_c} \right) \Big\} \, N_F\text{-}N_c$$

$$M = \begin{pmatrix} 0 & 0 \\ 0 & M_0 \end{pmatrix}$$

- One-loop effective potential stabilize the direction at (□, M_0)=($0,0$)



Plan of talk

First Part

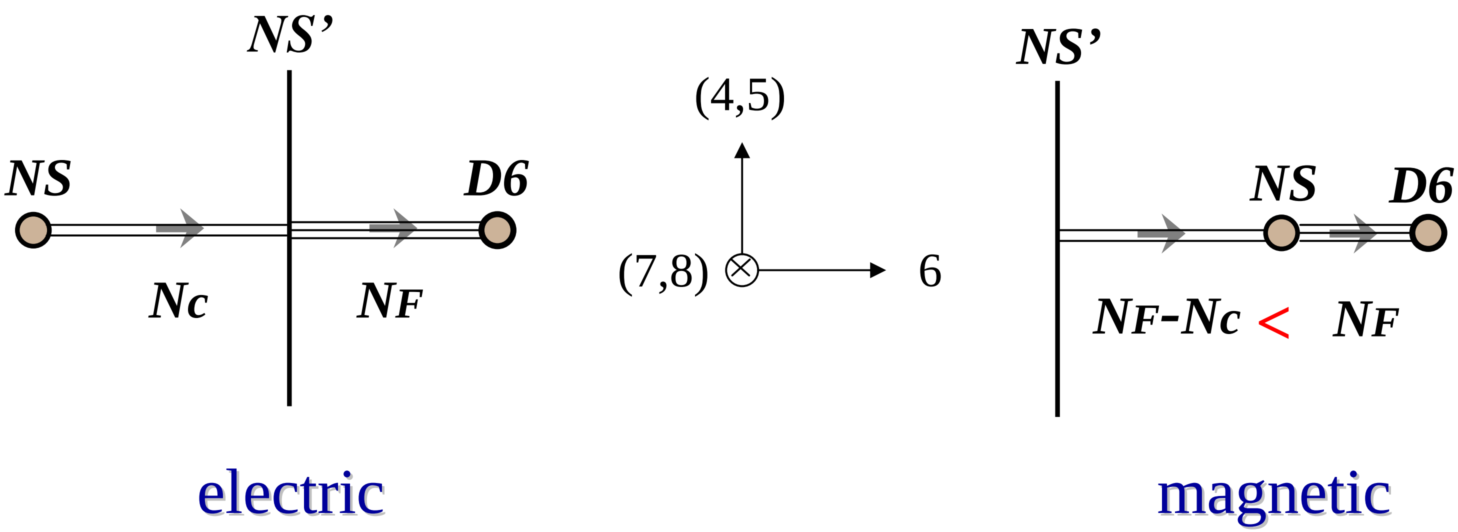
Intersecting Brane configuration in TypeIIA string

Second Part

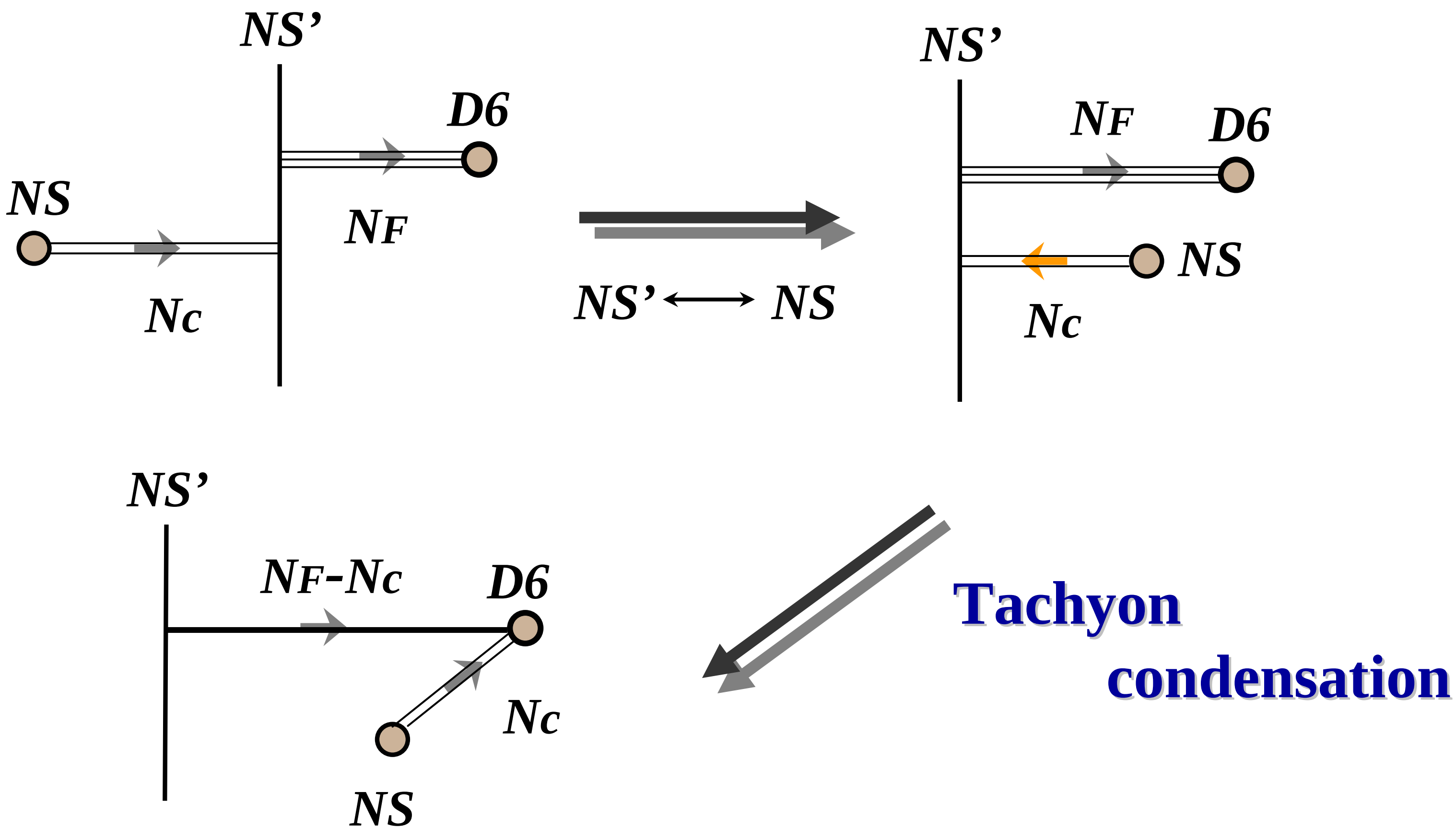
Model of direct gauge mediation
(Realistic model building)

D-brane configuration for ISS meta-stable vacua

- Brane configuration for massless SQCD
- Exchanging *NS5* branes give rise to Seiberg dual [Elitzur-Giveon-Kutasov]

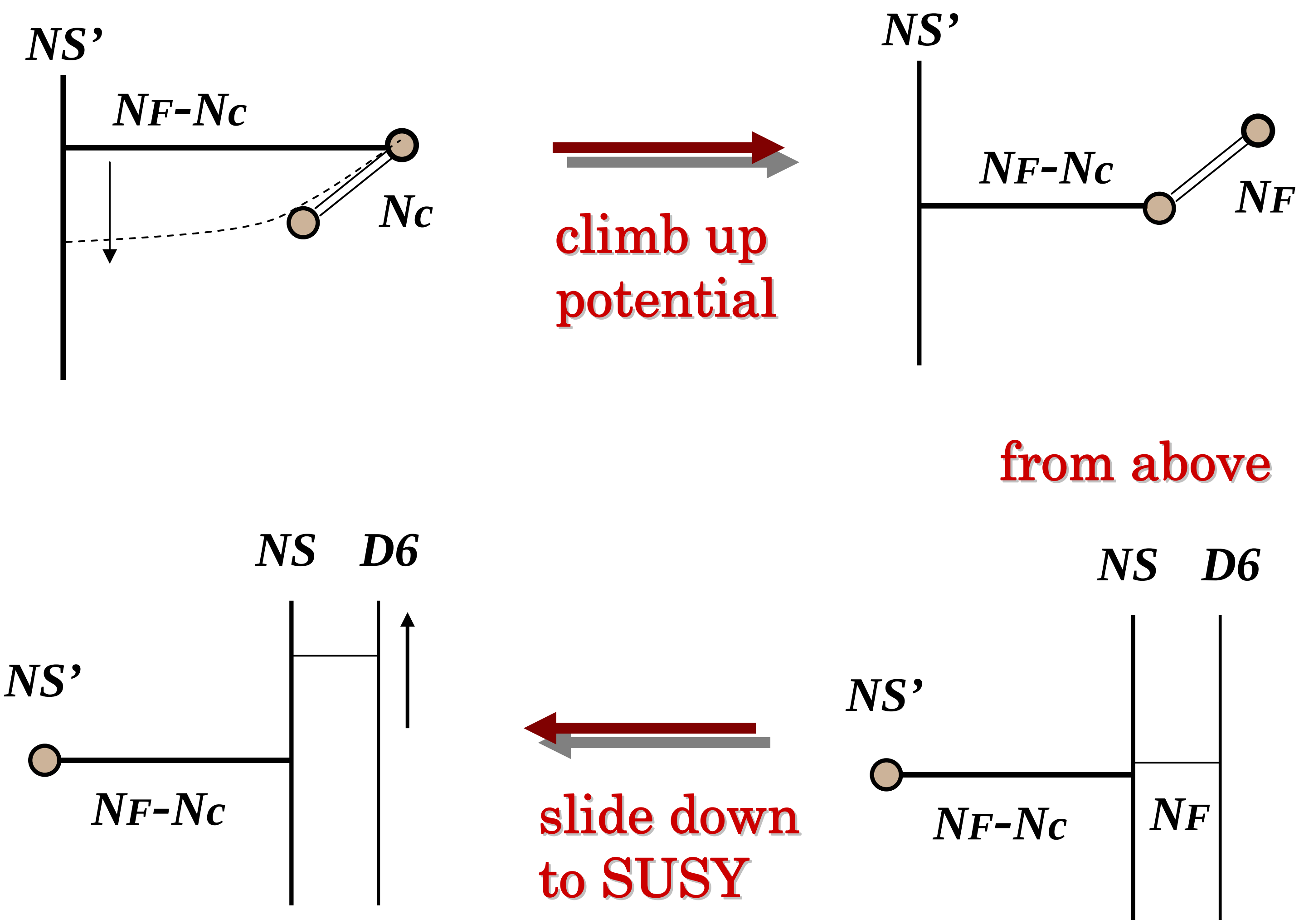


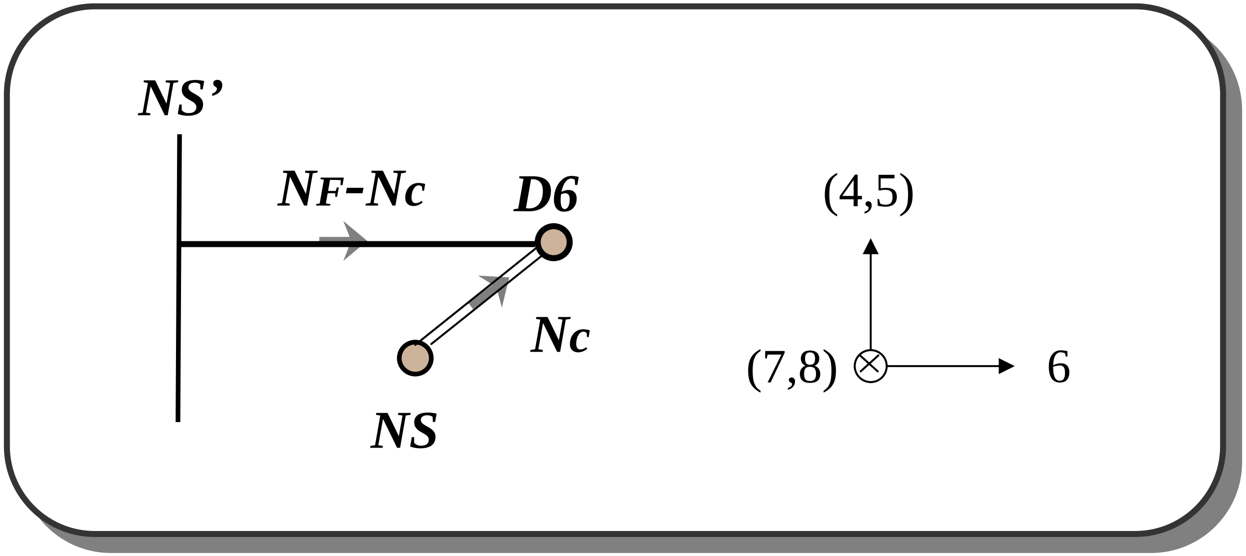
- *D6* brane is away from origin for Massive SQCD



- This configuration reproduces various features of ISS meta-stable vacua

Decay process: From ISS to SUSY vacua





- *D6* project out tachyon on intersecting *D4*
- Energy of SUSY breaking vacua
- Global symmetries including $U(1)_R$
- Vev of quarks and meson

$$q = \begin{pmatrix} \mu \\ 0 \end{pmatrix} \qquad M = \begin{pmatrix} 0 & 0 \\ 0 & M_0 \end{pmatrix}$$

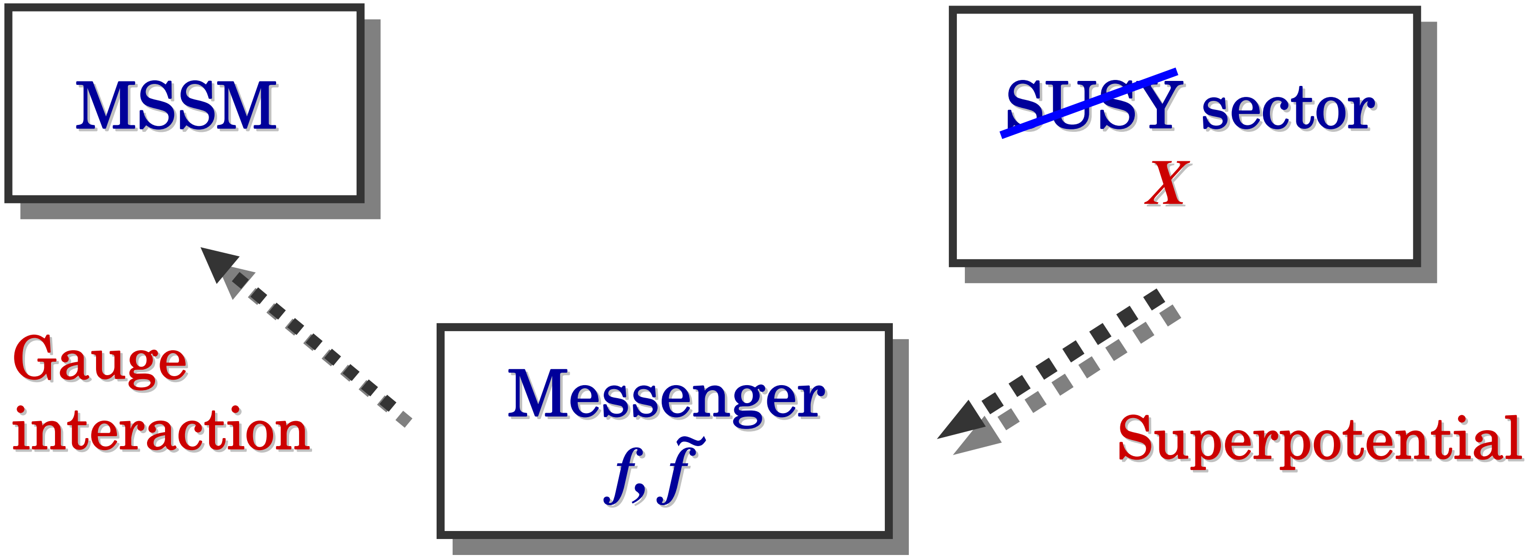
Second Part

Model of Direct Gauge Mediation

Gauge Mediation

Among several possibilities for mediation of SUSY breaking effect, gauge mediation seems better

- Low energy SUSY breaking
- Dynamics is well studied in 90s
- Flavor blind mediation (suppress FCNC)

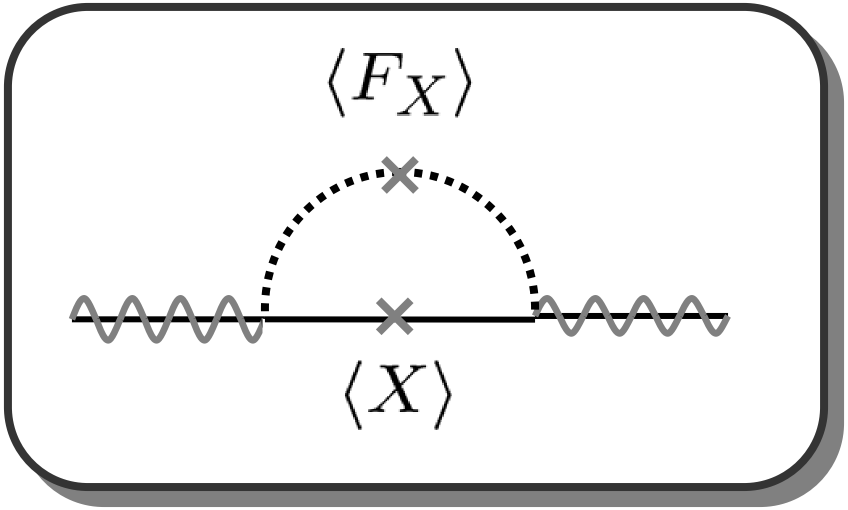


- Messengers carry SM charge and interact with SUSY breaking sector by Yukawa interaction

$$W = X f \tilde{f} \qquad \langle X \rangle = \langle X \rangle + \theta^2 \langle F_X \rangle$$

- Radiative corrections generate soft SUSY breaking terms including gaugino and scalar masses

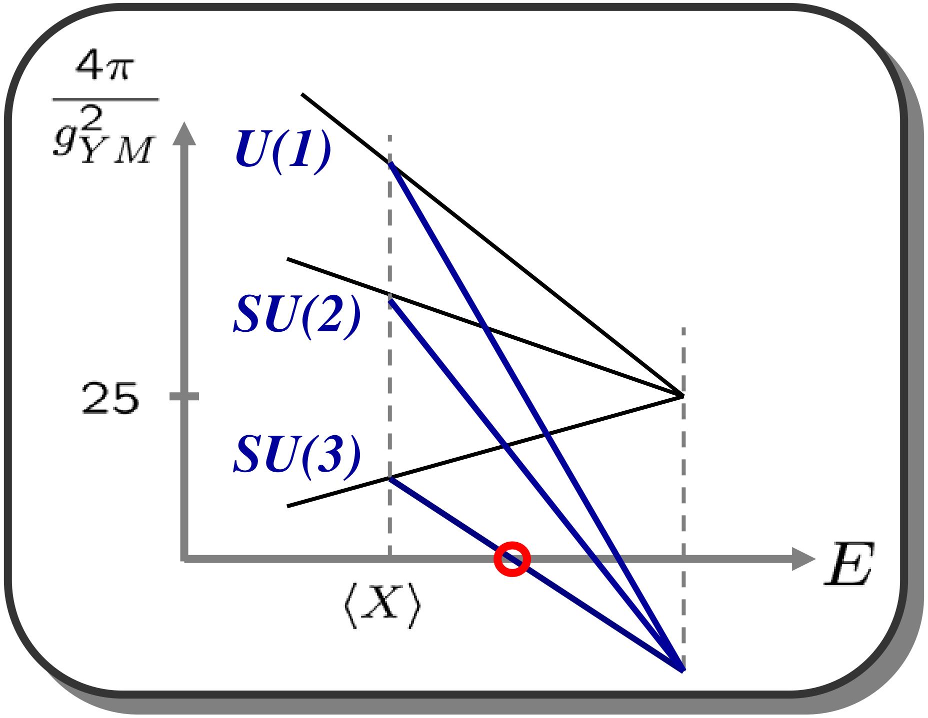
- Gaugino can get mass from one-loop correction if *U(1)R* symmetry does not exist
- Scalar mess is generated at two loop level



- Since we construct a model with meta-stable vacua, *U(1)R* symmetry is not needed
- We can add *R*-breaking term to SUSY breaking sector (No *R*-axion)

- Messengers contribute to running of coupling

$$b = -3C_2(G) + quark + T(R)(\# \text{ of } f)$$



- Including many messenger develops Landau-Pole below *GUT* scale (serious issue for direct-type model)

- By gauging subgroup of unbroken global symmetry *SU(n)* and identify with SM gauge group, SUSY breaking sector can directly couple to MSSM

$$SU(n) \supset SU(3) \times SU(2) \times U(1)$$

- Fields that carry charge of *SU(n)* are regarded as messenger and contribute to running of coupling (They might cause Landau pole problem)

Set up of Our Model

- Free magnetic range
- Modification of ISS by adding R-breaking term
- Global symmetries are $SU(N_F - N_C) \times SU(N_C) \times U(1)$

$$W_{ele} = \mu_e Q_2 \tilde{Q}_2 + m_e Q_1 \tilde{Q}_1 + \frac{1}{m_X} Q_1 \tilde{Q}_2 Q_2 \tilde{Q}_1$$

$$\begin{pmatrix} Q_1 \\ Q_2 \end{pmatrix} \cdot (\tilde{Q}_1, \tilde{Q}_2) \rightarrow \quad M = \Lambda_e \begin{pmatrix} Y & Z \\ \tilde{Z} & \widehat{\Phi} \end{pmatrix}$$

$$W_{mag} = \mu^2 \widehat{\Phi} + m^2 Y + m_z Z \tilde{Z} + \frac{M}{\Lambda_e} q \tilde{q}$$

$$\mu^2 \equiv \mu_e \Lambda_e, \;\; m^2 \equiv m_e \Lambda_e, \;\; m_z \equiv \Lambda_e^2 / m_X$$

ISS supersymmetry breaking vacua

$$q = \begin{pmatrix} me^{\theta} \\ 0 \end{pmatrix} \quad \tilde{q} = \begin{pmatrix} me^{-\theta} & 0 \end{pmatrix}$$

$$M = \begin{pmatrix} 0 & 0 \\ 0 & M_0 \end{pmatrix}$$

Non-compact flat directions

- Coleman-Weinberg potential lift all flat directions when

$$m_z < m$$

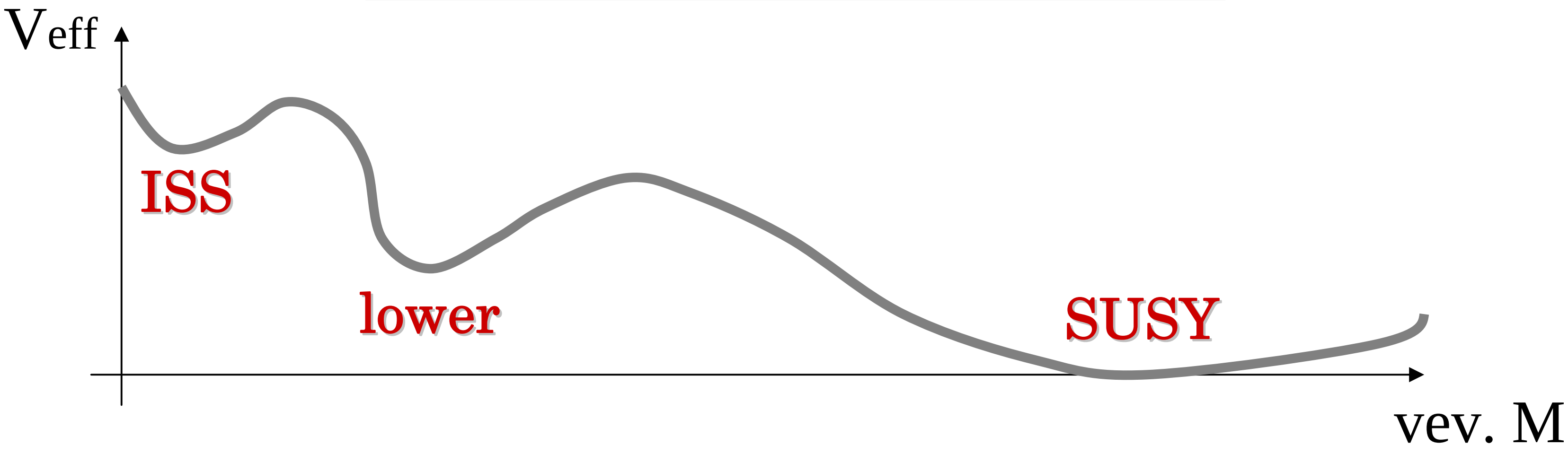
- Vev of ***M*** at stable point is non-zero because of R-breaking term

$$\langle M_0 \rangle \neq 0$$

Vacuum Structure

- SUSY vacuum is quite far away from ISS vacuum
- There are another meta-stable vacua with lower energy
- Transition probability is very small because of mass hierarchy $\mu \ll m$

$$e^{-S_E}, \quad S_E \sim \left(\frac{m}{\mu}\right)^4 \left(\frac{m}{m_z}\right)^4$$



Mass spectrum on ISS meta-stable vacua

- Goldstone boson of *U(1)* breaking
- Goldstino of SUSY breaking
- pseudo-moduli $\mathcal{O}(\mu^2/m)$
- Others $\mathcal{O}(m)$

Unbroken global symmetry

- $SU(N_F - N_C) \times SU(N_C)$
- Two possibilities of embedding of SM
- Embedding into $SU(N_F - N_C)$ is successful

Radiative corrections generate gaugino and scalar masses

$$m_\lambda = \# \frac{\mu^2}{m}\frac{m_z}{m} + \mathcal{O}(\frac{m_z^2}{m^2})$$

$$m_s^2 = \#^2 \left(\frac{\mu^2}{m}\right)^2 + \mathcal{O}(\frac{m_z^4}{m^4})$$

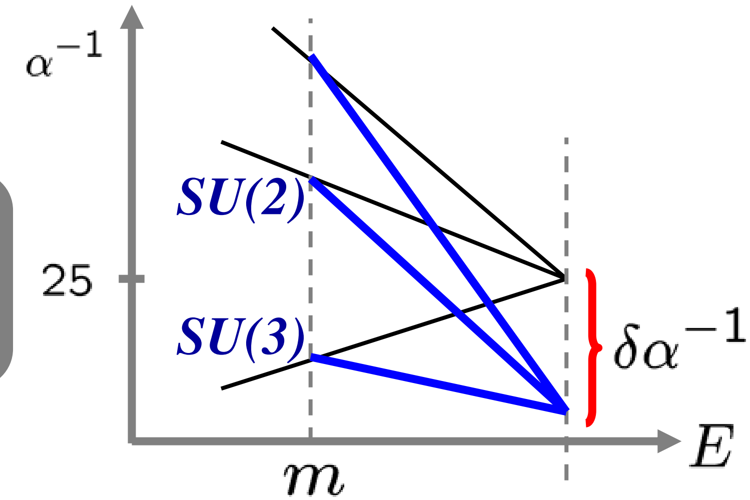
To avoid Landau-Pole we impose a condition

$Y, \ \tilde{Z}Z, \ \chi, \tilde{\chi}$ carry charges of SM gauge group

$$q = \begin{pmatrix} \chi \\ \rho \end{pmatrix} \qquad \mathrm{M} = \begin{pmatrix} Y & Z \\ \tilde{Z} & \widehat{\Phi} \end{pmatrix}$$

$$b_3 = -3 \cdot 3 + 6 + (N_F - N_C) + N_C + (N_F - N_C)$$

$$\delta\alpha^{-1} = \frac{2N_F - N_C}{2\pi} \ln \frac{M_{GUT}}{m} \leq 25$$



Any solution for all conditions?

$$N_C + 1 \leq N_F \leq \frac{3N_C}{2}$$

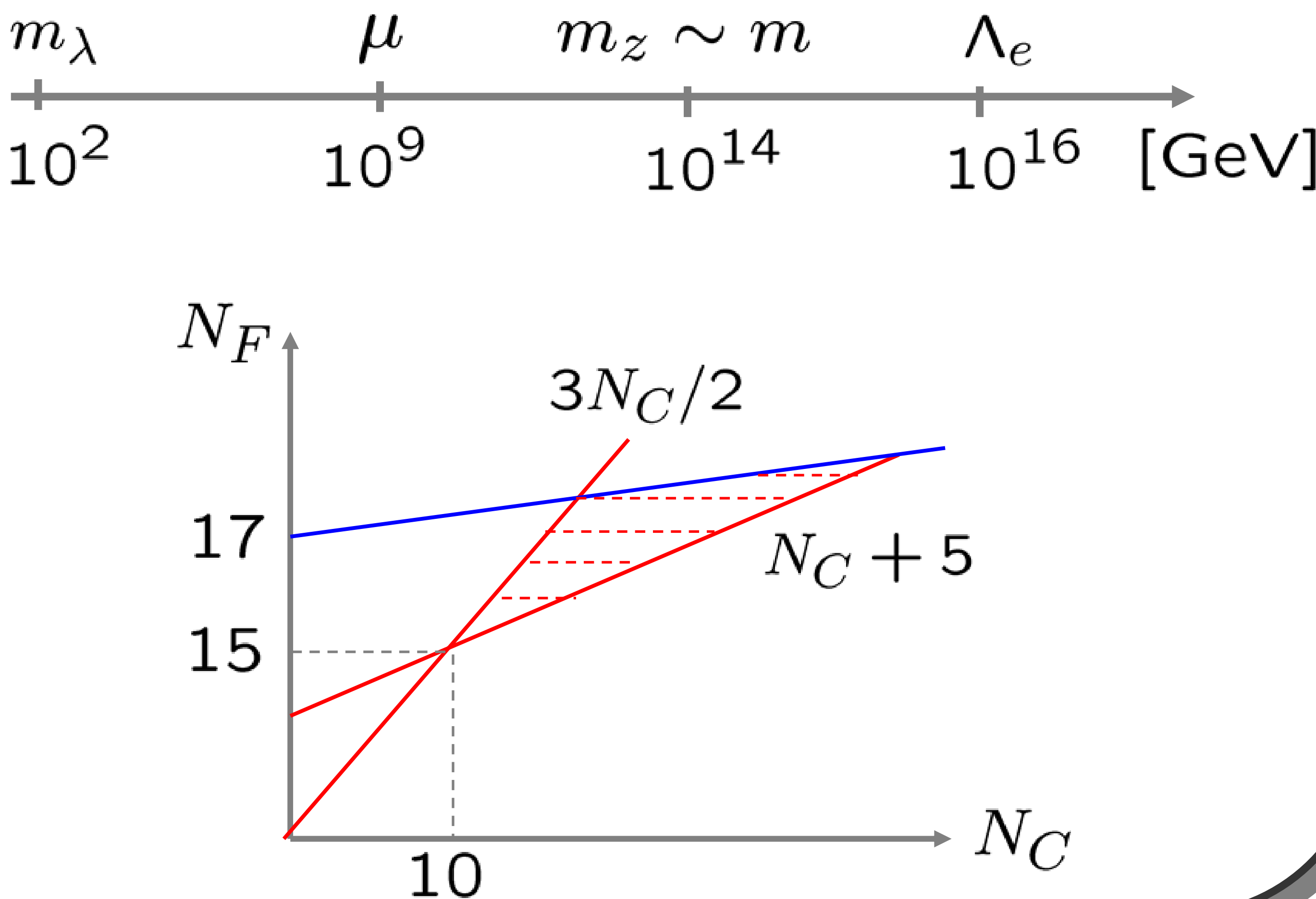
$$N_F - N_C \geq 5$$

$$\mu \ll m_z \sim m \ll \Lambda_e \ll m_X$$

$$m_\lambda \sim \mathcal{O}(100)\text{GeV}$$

$$\mu \leq 10^{9.5} \text{ GeV}$$

One example



m_λ
μ
$m_z \sim m$
Λ_e
10^2
10^9
10^{14}
10^{16}
[GeV]
N_F
$3N_C/2$
17
$N_C + 5$
15
N_C
10

UV completion

$U(N_1) \times U(N_2) \times U(N_3)$ **Quiver gauge theory**

$$\Lambda_1, \Lambda_3 \ll \Lambda_2$$

$$W = Q_{21}X_1Q_{12} - Q_{12}X_2Q_{21} + Q_{32}X_2Q_{23} - Q_{23}X_3Q_{32} + W_1 + W_2 + W_3$$

$$W_1 = \frac{m_X}{2}(X_1 - \mu)^2$$

$$W_2 = -\frac{m_X}{2}X_2^2$$

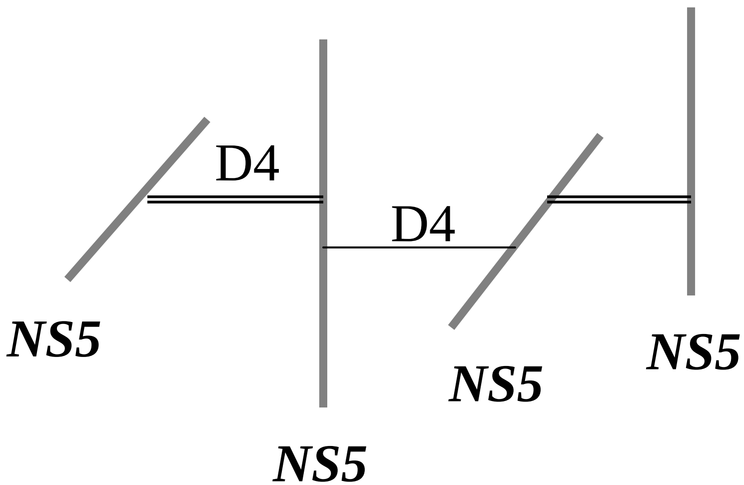
$$W_3 = \frac{m_X}{2}(X_3 - m)^2$$

As in Part I, we can construct electric and magnetic brane configurations of this model

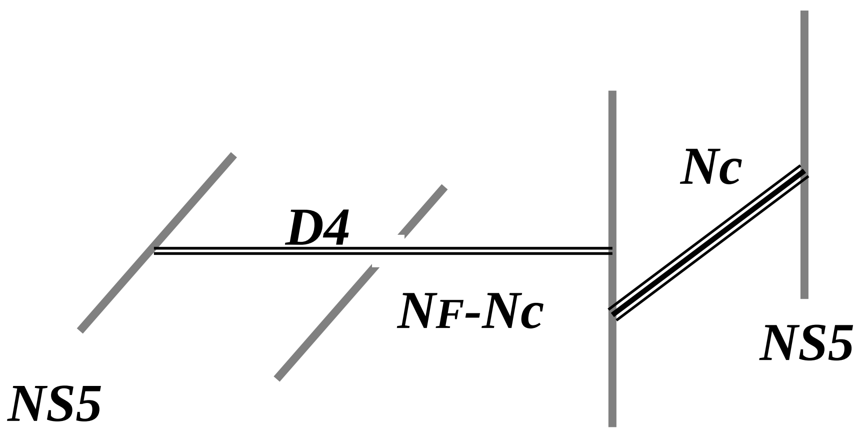
Also this model can be realized on *D5* partially wrapping S^2 in *CY 3*-folds

- Model of simple direct gauge mediation that can be realized in TypeIIA and TypeIIB string theories
- Phenomenologically successful (Landau pole, Soft mass terms)

electric description



magnetic description (ISS vacua)



Naturalness of our model

$$W_1 = \frac{m_X}{2}(X_1 - \mu)^2 \qquad W_2 = -\frac{m_X}{2}X_2^2$$

$$W_3 = \frac{m_X}{2}(X_3 - m)^2$$

- We tuned mass parameters in superpotential
  Is that natural?
- It is technically natural because soft SUSY breaking
  does not yields quadratic divergence

Approximate *U(1)R* symmetry

- From the low energy point of view, our model can be understood by approximate *U(1)R* symmetry
- Suppose that the breaking order is $\mathcal{O}(\mu_e)$
- Consider generic superpotential that has this symmetry *R(Q1)=1, R(Q2)=0*

$$m_e Q_1\tilde{Q}_1 + \frac{1}{m_X}Q_1\tilde{Q}_2Q_2\tilde{Q}_1 + \frac{1}{m_X^{2k-1}}(Q_2\tilde{Q}_2)^k(Q_1\tilde{Q}_1) + \cdots$$

$$\mu_e Q_2\tilde{Q}_2 + \frac{\mu_e}{m_X^{2k}}(Q_1\tilde{Q}_1)^k(Q_2\tilde{Q}_2) + \cdots$$

We should have added $Q_1\tilde{Q}_1Q_2\tilde{Q}_2$. This does not appear by integrating out of adjoint of *U(Ni) Xi (SU(N) case it appears)*